Chapter 1
Introduction: Agent-Based Modelling as a Tool to Advance Evolutionary Population Theory

Jan Van Bavel and André Grow

1.1 Introduction

Demography has for long and repeatedly been described as a field that is rich in methods but poor in theories (Burch 2003a; De Bruijn 1999; Tabutin 2007; Vance 1952). While there has been a lot of methodological advancement, the field has made less progress in generating widely accepted theories that explain trends in fertility, mortality, migration, or other aspects of population. Of course, to the extent that the dynamics of human populations are governed by the same kind of forces as other social processes, demographers can and do borrow theories from other social sciences. However, to the extent that important aspects of population processes really are a reality sui generis, the field would strongly benefit from more theory development.

More than 10 years ago, Billari et al. (2003) recommended agent-based modelling (ABM) as a tool to advance population theory. While a number of ABM-contributions have been published in the mainstream demographic journals since then, ABM still has not become a standard tool in every demographer's kit and the advancement of population theory through ABM still remains limited. Ironically, Billari et al. (2003, p. 3) already pointed out an important factor hindering the widespread application of ABM in population studies: the lack of theories. ABM proceeds by implementing theoretical rules of behaviour, decision-making, and interaction in a simulation and then investigates the resulting patterns that emerge from this. So, on the one hand, in order to apply ABM, one needs theory; on the other hand, we want to apply ABM in order to develop the theories we are lacking.

J. Van Bavel (✉) • A. Grow
Centre for Sociological Research, University of Leuven (KU Leuven), Parkstraat 45, 3000 Leuven, Belgium
e-mail: jan.vanbavel@soc.kuleuven.be; andre.grow@soc.kuleuven.be

A. Grow, J. Van Bavel (eds.), *Agent-Based Modelling in Population Studies*, The Springer Series on Demographic Methods and Population Analysis 41,
DOI 10.1007/978-3-319-32283-4_1

In this introduction, we want to highlight one reason for this ‘Catch-22’, namely the rather ‘closed’ concept of population that has been dominating the field. Most of the effort in demography has been devoted so far to the numerical monitoring of national population flows and structures. Not only has demography been preoccupied with empirical data and techniques for analysing these data (Burch 2003b), the field has also been preoccupied with data representing the populations of nation states. The requirement to have ‘nationally representative’ data has important advantages, but it has hindered creative theory development. The field should adopt a more ‘open’ approach to population to allow more flexible experimentation with theories. We will argue how ABM offers a tool to help bridging the gap between different approaches to the concept of population. Next, we illustrate some of the arguments with examples from chapters in this volume. Subsequently, we argue that evolutionary theory might be a particularly suitable theoretical framework for developing population theory aided by ABM.

1.2 Two Concepts of Population

In the course of its development over the nineteenth and twentieth century, an approach to population has come to dominate demography linked with a ‘closed’ concept of population. This approach prioritizes the descriptive coverage of nationally representative population indicators rather than understanding the underlying heterogeneity and processes (Kreager 2009, 2015a, b). Central to classic demography has been the accurate bookkeeping of humans in national populations. In the national demographic accounts, births and deaths represent the natural sources of population flow. Migration is considered from a national point of view as well, namely as outmigration from one country and immigration into another country. The basic demographic equation describes how both natural and migration flows affect the size and age structure of the population, and cohort component methods can be used to project it into the future. Getting the rates right is central to accurate national bookkeeping, depending on correctly counting the number of demographic events to put in the numerator and enumerating the relevant population in the denominator. The seminal work by Lotka and later developments in formal demography exemplify this ‘closed’ concept of population (Dublin and Lotka 1925; Schoen 2006).

This approach was closely connected with the rise of the idea of the nation state, where nations are defined by a delimited population, sharing territory, language, and historical experience (Kreager 2009, 2015a). It has been a powerful ally for the establishment (and national funding) of human demography as a field. The concept of the national population (and their smaller and larger scale derivatives) has stimulated demographers to develop ingenious methods to measure fertility and reproduction, mortality, and migration. It has inspired debates over things such as replacement level fertility, about whether the increase of the TFR from 1.5 to 1.6 in some country represents a quantum or a tempo shift, or about the impact of immigration on the structure of the population. Such measures and debates have enhanced our insight into important issues like population growth and decline, the relative role played by quantum and tempo shifts in demographic trends, or population ageing. This is great progress and looked at it in a specific way, it could be called theoretical progress too (see Burch 2003a). Many key insights from demography are important for the management of nation states and their institutions, as the long-standing debate about below-replacement fertility and its relation to population ageing illustrates (Van Bavel 2010a). Accordingly, demography has become an important field "in service of the state" (Kreager 2015b, p. S32).

The fact that the national population has become the dominant point of reference does not imply that demographers have failed to investigate variation within countries (cf. Billari 2015; Courgeau et al. 2016). Notably towards the end of the twentieth century, demographers have increasingly adopted regression analysis as a tool to investigate how fertility, mortality, and migration co-vary with things such as education, wealth, or religion. Courgeau et al. (2016) discuss more in depth the advances made in demography, from studying national aggregates over individual level modelling towards multilevel event history analysis, and they argue that these advances may even be considered as paradigm shifts. Still, the national population remained the standard point of reference, with analyses being carried out preferably based on nationally representative samples, and comparative studies being carried out between nation states.

While the 'closed' concept of the national population has been very instrumental in the establishment of the discipline, the rather rigid approach may have hindered the creative development of population theories. Methodologically, the dominance of this nineteenth century concept of population is reflected in the heavy reliance of demographic studies on either (single- or multi-country) census or nationally representative survey data – to such an extent that sound studies of demographic processes might be rejected due to a lack of 'representative data'. Similarly, theoretical work tends to be accepted as a serious scientific contribution only if its relevance could be shown, empirically, on a census or nationally representative sample (cf. Billari 2015). This is an extremely costly and inflexible requirement, discouraging creative experimentation with new ideas. It limits the room for more particularistic reasoning about how local conditions differentially affect certain groups and their relations with others (Kreager 2015a, p. 73, 2015b).

Kreager (2009, 2015a, b) has shown how the concept of the enumerated, national population as the standard point of reference got established at the expense of an alternative concept of population. In the alternative 'open' approach to population, the emphasis is not so much on enumerating all individuals who belong to the country, but rather on the processes and structures that emerge out of the interactions between heterogeneous individuals and their environments, embedded in social groups and networks. The main concern in the 'open' study of populations is understanding the processes and mechanisms that generate patterns of association between individuals, such as mating or social networks, and how these processes affect population change and heterogeneity. This alternative approach largely got lost in most of the mainstream work in human demography but it remained very strong in population biology. The detailed observation of particular species in their specific habitat by Charles Darwin exemplifies the alternative, more ‘open’ concept of population, and this has remained the dominant population concept in the Modern Synthesis in biology (Mayr 1991, 2002). While the emphasis in demography has been on averaging demographic behaviour in rates (typically for national populations and subpopulations) and calculating their long-term stable population implications, the emphasis in population biology has been on heterogeneity and change. In the words of Ernst Mayr: “The populationist stresses the uniqueness of everything in the organic world. What is true for the human species – that no two individuals are alike – is equally true for all other species of animals and plants. [. . .] [F]or the populationist the type (average) is an abstraction and only the variation is real” (Mayr 1959 cited in Mayr 2002, p. 92).

In order to understand the past, present, and future dynamics of populations as networks of interactions, it is insufficient to survey and analyse statistically cross-sectional snapshots of samples of individuals and their characteristics. Alternative and complementary modes of observation are needed, including the kind of local, small-scale observations to which Darwin devoted much of his life (Kreager 2009), or the kind of in-depth studies of local communities common in historical demography (e.g., Kertzer and Hogan 1989; Tsuya et al. 2010). A more ‘open’ approach to population may also integrate insights from experimental research, as a particular form of local, typically small-scale observations but with particular strengths when it comes to drawing conclusions about causality.

A move towards a concept of population as a fundamentally open and dynamic network of interacting individuals also calls for methods to study these dynamics in a flexible way. ABM is a useful tool to help opening up the ‘closed’ approach to population that has dominated the field. This, in turn, will help us to develop and refine our theories of population processes. More precisely, ABM may help us to bridge the ‘open’ and ‘closed’ concepts of population in a way that we may benefit from the advantages of both approaches while acknowledging their respective limitations.

1.3 How Agent-Based Modelling May Bridge the Two Approaches to Population

Demography studies populations of individuals who interact in complex ways in different layers of cultural and social environments. It often investigates emergent regularities of such individual-level contextualized behaviour. ABM lends itself quite naturally to deal with this complexity (Courgeau et al. 2016): ABM is population oriented and applying ABM starts with imagining a population of individual agents. Here, we want to highlight how ABM may bridge the two concepts of population that we have just outlined. It can do this while maintaining a view on both the micro (individual) and the macro (aggregate) level. In this way, it may help to address a major challenge in the development of population theory: "[H]ow to combine theoretical principles that operate at the local level with concepts of global population" (Hammel and Howell 1987, p. 142)? In order to see how this can work, it is useful to draw on the 'macro-micro-macro model' that is at the centre of the social mechanism approach to social theory (Coleman 1986, 1990; Hedström and Swedberg 1998; Hedström 2005) and which recently has been introduced to demography (Billari 2015).

1.3.1 The Macro-Micro-Macro Model and Agent-Based Modelling

The 'macro-micro-macro model' shown in Fig. 1.1 builds on the tradition of methodological individualism, in which social phenomena are viewed as the results of the actions of the individuals that make up the social system under consideration. Accordingly, proponents of the model argue that sound social science explanation should refer to these individuals and include explicit references to the causes and consequences of their actions (Hedström and Swedberg 1998, p. 12). In the model, explanations proceed in three steps. In the first step, an explanation indicates how the characteristics of the macro level affect the conditions and constraints that individuals face (situational mechanisms); in the second step, it indicates the way in which individuals assimilate these constraints and conditions in their behaviour (action-formation mechanisms); in the third step, it indicates how the actions and interactions of a large number of individuals bring about macro-level outcomes and social change (transformational mechanisms).

Applying this model to demography, Billari (2015) highlighted that the last step is the most novel and most important, but also the most challenging. It is most novel, because the first two steps have featured in existing demographic research. For example, the notion that the individual is affected by the characteristics of the macro

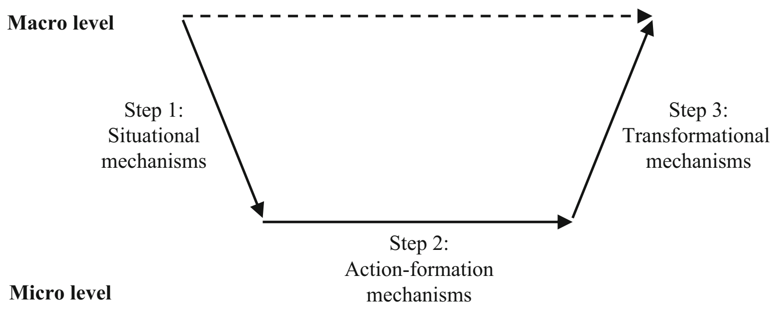

Fig. 1.1 The macro-micro-macro model in the social mechanism approach (adapted from Hedström and Swedberg 1998; Billari 2015)

level features prominently in the multilevel paradigm in demography; similarly, the notion that the constraints that individuals face affect their decisions and actions features in approaches such as life course analysis, in which the antecedents of people's behaviour lie in their own past (Courgeau et al. 2016). It is most important, because it reconnects the individual level with the macro level. It is most difficult, because the processes and dynamics by which individual interactions combine to generate macro-level outcomes can be very complex and this can make them very difficult to address with standard mathematical and statistical tools in demography.

For illustration, consider first the case of regression-based methods. The basic format for this approach is that an individual- or population-level outcome is "affected by" (Coleman 1986, p. 1328) a set of individual and contextual variables that are combined additively and linearly. Non-linearities in the relation between the different variables and the outcome are easily accommodated. Interaction effects between variables can be estimated too, in principle, but when several interactions between more than two variables are involved, then the model quickly becomes hard to handle. The goal of this approach is to find reliable statistical associations between the variables and the outcome, but it does not explicate the processes that underlie these associations. For example, a regression-based model can show that variation in the level of modernization is associated with variation in fertility rates across countries, but it does not explain how the two are connected through the actions of individuals. As noted above, multilevel models make it to some extent possible to model the way in which macro-level variables affect individuals, but even with this approach it is not possible to model the processes by which individual interactions feed back into the macro level. Williams et al. (2016) discuss additional problems that can arise from regression-based models. Similarly, econometric approaches, like instrumental variables and selection models, are geared toward isolating causal factors and assessing the extent to which the effect of variable X on variable Y testifies of 'true' causality. While this may sometimes be an important goal, also these models do not explicate the precise mechanism by which X and Y are connected.

Consider next mathematical models. An important question in demography is the role that social networks play for people's demographic decisions (Prskawetz 2016). The timing of entry into first marriage, for example, has been assumed to be affected by the number of peers who are already married. Hernes (1972) proposed a mathematical model that can show that the share of married individuals might indeed affect individuals' age-contingent probability to enter marriage. Yet, similar to regression models, this model does not explicate the processes and interactions by which individuals influence each other in their marital decisions (Hernes 1976). Even more, the model abstracts from social network structures that might exist in the population and that might affect the timing and spread of the diffusion process (cf. Cointet and Roth 2007).

For ABM, modelling transformational mechanisms and the interactions and network effects involved in this is at the core of the business. For example, as Klüsener et al. (2016) show, with ABM it is possible to implement socially and spatially segregated networks and this increases our ability to explain (spatial) diffusion processes. This makes ABM a promising tool to facilitate theory development in population studies. A second important quality of ABM is its ability to show "the consequences of a few simple assumptions" (Axelrod 1997, p. 206). Given the computational power that is currently available on standard personal computers, and given the increasing access that many researchers have to grid computing, ABM makes it feasible to conduct simple as well as more complex thought experiments and to quantify the implications of different assumptions. ABM can therefore be used as a powerful computational laboratory to conduct simple as well as complex 'what if' thought experiments in a flexible but precise way. As pointed out by Prskawetz (2016) as well as Courgeau et al. (2016), with ABM, 'toy models' may therefore be employed to (pre-) test theories for which data are not easily obtained or not (yet) available at all. In this process researchers are not constrained to theorizing on the interplay between the individual and the population level alone. As the chapter by Wolfson et al. (2016) illustrates, ABM makes it possible to also consider all possible levels in between (e.g., schools, neighbourhoods, etc.). This flexible scalability (see Miller and Page 2007, pp. 85–86) enhances the opportunities for theory development, since theories can be developed at any level, while the implications of the theory for phenomena at other observational levels can then be computed.

This potential to conduct complex thought experiments does not mean that ABM should replace standard tools in demographic research and empirical data altogether. Quite to the contrary, we concur with Courgeau et al. (2016) that for making use of the full potential of ABM in demographic research, the connection with earlier modelling techniques is important. Such a connection enables to create empirically calibrated agent-models that have more realism and validity than purely theoretical simulation models.

1.3.2 Empirical Calibration

Calibrating agent-based models with empirical data is an important step in developing explanations of demographic change (Bijak et al. 2013; Courgeau et al. 2016; Hedström 2005). Such more advanced modes of computational experiments mixed with observational data can take the following basic form: (1) develop a theoretical model based on assumptions about individuals' actions and interactions; (2) calibrate the model to match empirical data; and then, crucially, (3) conduct 'what if' experiments: what would happen if we leave out parameter X? How would things change if the empirical distributions would have been different than they are under actual conditions? And what if individuals behaved differently? In this way, after calibration, it is possible to perform counterfactual simulations that help advocating between possible alternative processes.

Many chapters in this volume provide examples of empirical model calibration. For example, Deconinck et al. (2016) draw on existing studies and expert knowledge to calibrate their model of severe acute malnutrition in terms of important population parameters, thresholds, and decision processes. Kluge and Vogt (2016) use realistic demographic rates (e.g., age-specific death rates and transition into public pensions) to study how intra-familial transfers might help explaining observed patterns of old-age survival. Similarly, Williams et al. (2016) develop an agent-based model of the relation between armed conflicts and population change, in which key individual-level decision processes are implemented as probabilities estimated from a combination of survey and register data, which can be conceived as "evidence-based action rules" (Hedström 2005, p. 132).

An application where the combination of theory-driven ABM with empirical data may prove to become particularly useful for demography is in the field of population projections and forecasts – one of the key areas of applied demography, closely linked with nation state oriented demography using a 'closed' concept of population, as discussed above. Projections proceed by calculating the implications of a set of theoretical 'what if' assumptions about demographic rates; forecasts have the ambition to yield realistic predictions about actual population trends in the future. So far, forecasts as well as projections typically extrapolate macro-level trends without being based on clear theories about the underlying micro-level behaviour. ABM may help to improve this. While Prskawetz (2016) reminds us that explanation rather than prediction is the primary purpose of ABM, she still hints at how it can be used to improve demographic projections when she discusses the model presented in Aparicio Diaz et al. (2011) about the transition to parenthood. This highlights the potential of ABM to use theoretically informed simulation models to generate potential population trends rather than just relying on extrapolations of past and ongoing aggregate trends (Prskawetz 2016). ABM may also be instrumental in integrating classic scenario-based projections and more recent probabilistic approaches (Lutz and Goldstein 2004; Willekens 1990; Wilson and Rees 2005). Classic scenario-based projections are mechanistic and fail to quantify uncertainty. ABM offers the opportunity to really simulate scenarios while accounting for heterogeneity on the individual level, including random components and probability distributions, and to see what macro-level population patterns emerge. To facilitate this process, researchers can rely on advanced statistical tools that make it possible to systematically explore the uncertainty that exists in the outcomes of the agent-model, as illustrated in the methodological chapters by Hilton and Bijak (2016) and Grow (2016).

Evidently, increasing the integration of empirical data and existing methods with ABM will also pose new challenges in terms of the complexity of the modelling process. Richardi and Richardson (2016) provide an example of how some of these challenges can be overcome with a new software tool that makes it possible to combine micro-simulation with agent-based models and that allows easy data handling.

1.3.3 Avoiding Potential Pitfalls

In the end, any theory and model, as well as population forecasts, will have to be tested with empirical data. In the empirical testing of an ABM, it is important to keep in mind that the ability of the model to simulate (or 'to grow') an observed empirical pattern is far from sufficient proof of its validity (cf. also the chapter by Courgeau et al. 2016). It is *not* sufficient to show that an ABM can produce results that are compatible with some set of observed data because the model may contain so many parameters that it can be fitted to any set of data (Grimm et al. 2005). Or, as rightly pointed out by Smaldino and Schank (2011, p. 13), "if there are no empirical constraints on assumptions, almost any results can be generated from different decision rules by varying assumptions about the environmental structure". The problem is that the model may be too flexible to draw firm conclusions about its validity; that there are too many degrees of freedom. The example provided by Smaldino and Schank nicely illustrates the issue: they show that very different models, involving very different but plausible decision-making rules involved in human mate choice, may all explain equally well the typical right-skewed distribution of age at marriage (i.e., the distribution that was also targeted by Billari et al. 2007 and Todd et al. 2005). The fact that a set of mechanisms implemented in an ABM is able to explain some patterns of empirical observations, even if all the available evidence has been used to calibrate the model, is therefore insufficient proof that these mechanisms actually generated these patterns.

The challenge of having 'too many degrees of freedom' may look like a limitation of ABM at first sight, but equivalent challenges apply to any kind of modelling. Conventional statistical models face similar challenges: very different models might fit the data equally well and a statistically significant 'effect' may actually be spurious, even when we have a plausible theory to portray it as a causal effect. Attacking ABM because it would claim to replace the role of empirical observation in the scientific endeavour (like Venturini et al. 2015 do) is therefore an attack on a straw man and misses the point. There is no antagonism between ABM and empirical observations. The one cannot replace the other; to rule out alternative scenarios and parameter values, scientists will still have to confront the model with empirical data that can help making the distinction.

There are two general ways in which a model can be confronted with empirical data to assess its validity. First, if there is a lack of empirical data, a model developed during the stage of theory formulation may guide subsequent data collection to advocate between model alternatives (cf. also Courgeau et al. 2016). In this step, ABM can also make the data collection effort more efficient, by sorting out potential candidate mechanisms *before* any data is collected. The chapter by Gray et al. (2016) in this volume illustrates this point. Given the lack of empirical data on how women decide whether or not to disclose their drinking behaviour to midwives, the authors explore several plausible decision mechanisms derived from existing decision theories. Their results suggest that there are characteristic differences in the results that the different decision models generate and this information can guide future data collection efforts to advocate between them.

Second, if empirical data does already exist, researchers can assess whether the model does not only reproduce the target outcome, but also other outcomes that were not in the focus of model development. This form of 'pattern-oriented modelling' (Grimm et al. 2005) aims at assessing the structural realism of models and helps to find the optimal zone of model complexity: addressing multiple patterns helps avoiding models that are too simple in structure and mechanism, or too complex and uncertain due to the high number of parameters. The agent-based model developed by Grow and Van Bavel (2015a) provides an example of such structural realism. The model was developed and calibrated with the goal to generate realistic patterns of educational assortative mating in the light of changing educational attainment in Western industrialized countries. Although patterns of divorce were not a target during the development of this model, Grow and Van Bavel (2015b) could show that it is able to also predict recent trends in divorce.

Summing up, the ability of a theory, implemented in an ABM, 'to grow' an empirically observed pattern or trend from the bottom up is insufficient to consider it a scientifically sound explanation. Such an ABM may be nothing more than 'a good story', while other stories may explain the empirical observations just as well. As always, the job on the to-do list then is to come up with clever ideas to set up a competition between different explanations and to collect new data that may differentiate between the right and the wrong story.

1.3.4 Bridging the Gap

We have emphasised that ABM allows linking the micro with the macro level and that its theory-based simulation approach allows computing the implications of hypothetical and empirically informed rules of action and interaction on the macro as well as the micro scale, and all scales in between. In practice, then, bridging 'open' and 'closed' concepts of population by means of ABM might work in two major steps. The first step consists of the in-depth study of actions and interactions in local populations, including rare events and exceptional instances as well as experiments. In combination with pre-existing theoretical frameworks and insights from earlier work, rules of behaviour and interaction (between individuals as well as with the environment) may be implemented in the simulation model. Already in this first step, ABM may be used for computational experimentation and to calibrate a model that is able to replicate ("grow", Epstein 2006) the local observations. In a second step, ABM is used to simulate the micro- and macro-implications of hypothetical rules of action and interaction outside the original context. Part of the work involved in this second step, in order to make the jump towards quantification in a closed population, is to infuse the models with real-life observational data, which in demography will notably be information about the distribution in that closed population by variables such as age, sex, and education (see Grow and Van Bavel 2015a for an example), i.e. exogenously infusing the ABM with information from traditional demographic approaches in order to make the model demographically realistic. It is only when the model is shown to work outside the context of where it was originally developed that its external validity can be demonstrated (cf. Hedström and Swedberg 1998).

To illustrate this process, consider psychological research that, more than any other field within the social sciences, has a long and rich tradition of conducting experimental studies to test theories. In combining 'open' and 'closed' population concepts, such experiments can be a first step to gain insights into individual behaviour and decision processes under controlled conditions. One shortcoming of such experiments is that they are often based on convenience samples, with undergraduate college students heavily over-represented in the data gathered, and focus on behaviour under sometimes unrealistic conditions. To avoid that the theoretical claims tested in such experiments hold only true for "the weirdest people in the world" (cf. Henrich et al. 2010) in the artificial context of the laboratory, a second step is needed. This second step does not just consist of collecting the same kind of samples as in the original experiments to check whether the predictions hold true in other samples as well. The true test of the theory is to study the patterns that the theory implies at other levels of observation and in the context of different populations. If the theory can correctly predict patterns at other levels of aggregation and for contexts in which the theory was not originally developed, this indicates the validity and structural realism of the model and underlying theory (Grimm et al. 2005; Hedström and Swedberg 1998).

To further illustrate this process, consider a specific example from the field of population studies. In today's Western societies, in which feelings of mutual attraction are considered a key determinant of heterosexual marriage, knowledge about the characteristics that men and women prefer in each other is crucial to understand how observed marriage patterns come about (cf. Buss et al. 2001). Over the last years, research in sociology, psychology, and economics has devised ingenious ways to gain insights into these preferences, for example, by use of census and survey data (e.g., England and McClintock 2009), vignette studies (e.g., Greitemeyer 2007), and speed dating experiments and procedural data generated by online dating platforms (e.g., Skopek et al. 2011). Apart from census data and national representative surveys, none of these sources could be considered congruent with the 'closed' concept of population dominating in demography. Yet, as Grow and Van Bavel (2015a) have shown, the insights gained from such small scale and highly detailed studies can help formulating theories about mate search and processes involved in union formation. ABM makes it possible to compute the implications of these theories, which can then be compared with empirical data observed in another context than the one that first inspired the theories, namely national marriage markets.

1.4 Contributions to Agent-Based Modelling in this Book

The chapters in this book address many of the issues that we have outlined up to this point. The chapters in the section 'Perspectives on Agent-Based Modelling in Population Studies' discuss in more detail the tasks that lie ahead and the steps that need to be taken to connect the 'closed' and 'open' concepts of population. They also highlight the benefits that agent-based modelling might yield in this process. The integration of empirical data and ABM will require some methodological advancements and the chapters in the section 'Designing, Analysing, and Reporting Agent-Based Models' illustrate some of the most recent developments in this direction. As argued earlier, ABM requires theories about individual behaviour and the chapters in the section 'Modelling Decision Processes' illustrate in detail how existing theories can be adjusted and implemented in agent-based models. Finally, the chapters in the sections 'Family Formation and Fertility' and 'Health, Mortality, and Support in Old Age' provide applied examples of how ABM can be fruitfully used to study demographic phenomena. In this section, we briefly review each of the chapters.

1.4.1 Perspectives on Agent-Based Modelling in Population Studies

In Chap. 2, Courgeau et al. (2016) trace the methodological developments in demography over its 350-year history and suggest that the introduction of model-based approaches to the field, such as ABM, constitutes a paradigmatic shift. This shift results from an increased interest in individual behaviour and interactions in population research and the authors highlight that in contrast to ABM, the hitherto dominant methodological approaches do not make it possible to model the 'two-way flow' between the micro and the macro level. Yet, they also highlight that ABM should not be seen as an alternative to other, more empirical methods in demography. Instead, in their outline of a possible research agenda for model-based demography, they make the strong point that there needs to be a close connection between empirical research and ABM. This ensures that the insights into population dynamics that ABM might yield are firmly grounded in empirical evidence and are not based on arbitrary assumptions that are disconnected from reality.

In line with some of the views outlined by Courgeau et al. (2016), in Chap. 3 Prskawetz (2016) points out that there is increasing consensus in that individuals' demographic decisions cannot be explained in isolation of the networks they are embedded in. She argues that ABM is particularly suitable to study such network effects from the bottom up and subsequently illustrates this capability of ABM with examples from her own work. Along the way, she discusses some of the central decisions that need to be taken when developing agent-based models; this will provide valuable guidance for novices to the field. In the last example, she also highlights the capability of ABM to conduct ‘what if’ experiments and illustrates the usefulness of this possibility by showing how it can be used to assess potential policy implications.

1.4.2 Designing, Analysing, and Reporting Agent-Based Models

In Chap. 4, Richiardi and Richardson (2016) provide a step-by-step guide for a new open-source, Java-based simulation platform, JAS-mine, that makes it possible to easily combine aspects of micro-simulation models with aspects of agent-based models. The development of this platform was instigated by the observation that although micro-simulation and ABM have been developed with different goals (i.e. data-based forecasting based on probabilistic regression models vs. theory development and understanding with a focus on interactions between individuals), they also share important commonalities, such as that they are discrete-event simulations, are recursive, and that the states of individuals evolve over time. Both approaches have their unique strengths that JAS-mine aims to combine, while at the same time providing a convenient structure to separate the modelling process from the data recording process. Such developments in ABM software will greatly facilitate the grounding of agent-based models in empirical data.

In Chap. 5, Zinn (2016) illustrates how an integration of micro-simulation models and ABM, as addressed by Richiardi and Richardson (2016), can be achieved. As she points out, micro-simulation lends itself to conducting fine-grained population projections under the assumption that individuals do not interact with each other. If this is combined with ABM’s capability to model social relations and interactions, it becomes possible to model life courses of both individuals and couples at the same time. For this, Zinn relies on the ml-DEVS formalism and implements the model in the simulation framework JAMES II. Her exemplary analysis attests to the potential of this approach and her work provides a frame of reference for those interested in combining micro-simulation with ABM.

Next to having the technical possibility to infuse agent-based models with empirical data, it is important that the field develops ‘best practices’ as to how empirical data should be used. In Chap. 6, Williams et al. (2016) provide one of the first steps in this direction. Drawing on related research in geographic and land use sciences, the authors illustrate how various sources of information (in particular survey data) can be used to implement a detailed representation of a specific population, both in terms of structure and decision processes. They also illustrate how the resulting model can be used to conduct ‘what if’ experiments to gain deeper insights into the processes that underlie observed population changes.

Even if a model has been calibrated with empirical data, there often is uncertainty in terms of how different model aspects (i.e. different parameters) relate to model outcomes and under which conditions the model actually is able to reproduce observed population patterns. One way to deal with this uncertainty is by the systematic design of simulation experiments combined with metamodels. In a nutshell, metamodels treat a simulation model as a black box and express the relation between model inputs and outputs by means of a statistical function. In Chap. 7, Grow (2016) illustrates the use of metamodels based on ordinary least squares regression analysis, whereas in Chap. 8 Hilton and Bijak (2016) illustrate the use of Gaussian process emulators. As the authors point out, metamodels based on regression analysis are an efficient tool to explore and describe input/output relations that can be described with polynomials. Gaussian process emulators make it possible to describe even more complex input/output relations and provide additional information about model uncertainty.

As Courgeau et al. (2016) argue, theory development by means of ABM will require explicit documentation of the way in which the simulation model was constructed and what assumptions guided this process. In Chap. 9, Groeneveld et al. (2016) review existing practices of model description in demographic research and come to the conclusion that so far no standard has emerged. After making the case that standardized descriptions can yield many benefits (e.g., enhanced replicability), they suggest the ODD+D standard as a possible candidate. Based on their experiences with an exemplary application to a demographic ABM, they also make recommendations as to how the standard could be adjusted to accommodate some aspects specific to demographic simulations.

1.4.3 Modelling Decision Processes

In developing agent-based models, researchers often have to draw on theories that were not developed with a procedural and dynamic focus. In Chap. 10, Willekens (2016) shows how existing theories from other fields of social research can be adjusted to better fit with the process-orientation of ABM. He uses the theory of planned behaviour to model the decisions that underlie international migration. For this, he extends the theory, so that it takes into account that the decision to migrate has a (random) processual character: the decision consists of several stages and it takes individuals time to transition from one stage to the other, contingent on systematic and random factors. He parametrizes the resulting simulation model with data from the Gallup World Poll 2005 and other sources and shows that it reproduces some stylized facts of international migration.

Agent-based models are often criticised for being based on ad hoc assumptions about individual behaviours and decision processes. In Chap. 11, Gray et al. (2016) address this issue by drawing on a long tradition of research in decision theory for modelling women's decision to disclose alcohol consumption during pregnancy to midwives. The authors frame the decision as a game theoretic problem in which both women and midwives are uncertain about the motivations and behaviours of each other. In the resulting signalling game, the authors compare four different decision models that differ in the complexity of the representation of the decision process within individuals. The results of the simulation experiments show that the different rules lead to somewhat different outcomes and therefore also lead to different recommendations for ways to enhance disclosure by women. This highlights the need to collect additional detailed data in this area where empirical insights are so far limited.

1.4.4 Family Formation and Fertility

In Chap. 12, Kashyap and Villavicencio (2016) explore the mechanism that might explain the rise in the sex ratio at birth (measured as the number of males per 100 females) that has accompanied the fertility decline over the last decades in Asia and the Caucasus. Congruent with earlier theoretical research, the model conceptualises sex ratio imbalances as the result of an interplay between son preferences, technology diffusion, and fertility decline. Using UN data to validate the model in the contexts of South Korea and India, one of the central insights of this study is that even if son preferences would have declined, an increase in the sex ratio at birth can arise from an increase in the accessibility of techniques that make sex-selective abortion possible combined with a decrease in total fertility levels. An important strength of this study is its cross-national approach, that attests to the generality of the processes that are modelled.

In Chap. 13 Klüsener et al. (2016) study the role that socially and spatially structured communication and influence processes might have played in the historical fertility decline observed in Sweden between 1880 and 1900. The chapter illustrates how the creative use of available census and GIS data facilitates conducting 'what if' experiments that help to uncover some of the processes that might have contributed to observed changes in (historical) populations whose members (and their interactions) cannot be studied in depth anymore. The results suggest that their diffusion model can reproduce many of the spatiotemporal properties of the observed fertility decline. In Chap. 14, Ciganda and Villavicencio (2016) also explore the mechanisms that might have generated observed trends in fertility, but in a more recent time period (1944–2014) in Spain. The authors model these trends as the outcome of an interplay between educational expansion (increasing the average opportunity costs for having children), increasing economic uncertainty, and social influence processes. The model illustrates how effects from factors exogenous to the social interactions under consideration can be amplified by precisely these interactions.

1.4.5 Health, Mortality, and Support in Old Age

In Chap. 15, Kluge and Vogt (2016) employ the case of the German reunification in 1990 as a natural experiment to address the question whether the positive association between income and old-age survival comes about through the goods and services that income can buy, or through third factors that affect both. In their modelling efforts, the authors focus on intra-familial exchange as a potential source of the observed association and draw on a variety of data sources for calibrating the model. Interactions occur within families and concern the exchange of income of parents for care from their children. The model can generate part of the observed changes in old-age survival in Eastern Germany after reunification and suggests that this increase might be partially caused by an increase in purchasing power and an increase in intra-familial exchanges.

In Chap. 16, Deconinck et al. (2016) show how ABM can be used to inform intervention strategies to reduce the effects of severe acute malnutrition. The authors highlight that the design and study of such interventions suffers from a lack of data and understanding of health system dynamics. They suggest that the theoretical, rule-based nature of ABM makes it possible to study factors that might potentially affect the effectiveness of interventions despite lack of data. For this, it is central to involve subject matter experts and practitioners in the model development process, to create accurate representations of the decision rules and interactions that occur in the actual system and to raise awareness among potential stakeholders.

In Chap. 17, finally, Wolfson et al. (2016) study the puzzling observation that in the US there exists an association between city-level income inequality and mortality, whereas no such association exists in Canada. Their main intuition is that this difference might be caused by the fact in US cities income segregation tends to be higher than in Canada. That is, in the US, there is more residential segregation in terms of income than in Canada and this might indirectly affect mortality rates through the properties of the communities (e.g., school quality) that feed back into the individual characteristics relevant for mortality (e.g., educational attainment). Using a simulation model that incorporates interactions between aspects of different layers of society (i.e. individuals, families, neighbourhoods, and cities), the authors find that their model is indeed able to generate patterns of mortality that are similar to those observed in reality, but for reasons that are different from what they expected.

1.5 Towards Evolutionary Population Theory

As we have indicated earlier, ABM is a useful method to help developing population thinking. The method itself is agnostic about the theory that is used to reason about the mechanisms that link the micro and the macro level. The diversity of the theoretical approaches used in the chapters of this volume attest to this flexibility of ABM. Yet, if demographic phenomena are phenomena sui generis, what kind of theory can we reasonably be looking for to explain them? In this closing section, we describe why we think that evolutionary theory is a particularly attractive candidate for this. Note that this represents our view, which does not necessarily represent the views of the other contributors to this volume.

1.5.1 The Basic Tenets of Evolutionary Theory

Inspired by thermodynamics, Lotka (1945) still had a concept of theory in mind consisting of a system of "laws" within which, "by the application of relatively few fundamental principles, the course of events can be rigorously *deduced* for innumerable specific situations" (Lotka 1945, p. 172, italics as in original). However, "demography is neither theoretical physics nor is it mineralogical chemistry": with this truism, Charbit (2009, p. 48) wants to highlight something he thinks is particular for the human sciences: because demography is a human science, theories are based on factors that are peculiar to a given historical context. Indeed, doing social science is not about finding eternal laws that allow us to predict the future. It might therefore be tempting to dismiss altogether the idea of a general theory of population and to stick with idiosyncratic narratives that might explain in a particular context why things happened the way they did.

Although we agree that historical peculiarities do and should play a role in social scientific research and theory, one could also argue that this epistemological point of view reveals a lack of ambition for the social sciences. Why would this argument hold for the social sciences and not for the biological sciences? Aren't plants and animals, in their phenotypic appearance and behaviour, also peculiar to their historical environment? It is precisely the uniqueness of every plant and animal that is highlighted in the populationist biology inherited from Charles Darwin (Mayr 2002, pp. 90–93). Darwinian evolutionary theory can be considered superior to the earlier, essentialist ways of theorizing about biological diversity because it is able to account for the changing biological diversity and developments that occurred in time not only before, but also after the formulation of the theory (Boyd and Silk 2009; Mayr 2002); it is able to "describe and explain phenomena with considerable precision", even if it cannot make reliable predictions about the future (Mayr 1961, p. 1504).

While demography and evolutionary biology have followed very different and increasingly divergent pathways after the Second World War, a Darwinian renaissance got started in recent decades, with an increasing number of papers inspired by evolutionary theory being published in mainstream demography journals (Sear 2015a). It would be good to intensify the conversation between demography and evolutionary theory. We concur with Sear (2015b) that the endorsement of evolutionary demography does not at all imply that evolutionary theory would be the only theoretical framework that has value in explaining demographic behaviour, but rather that it can inform, enrich, and stimulate theory development in our field.

The key ideas of evolutionary theory in biology are simple, but nevertheless often poorly understood: in a nutshell, organisms evolve through variation and differential selection. No two living organisms are exactly the same; for both genetic as well as environmental reasons, there is always variation. Not all variants survive and produce offspring in the next generation to the same extent. Those variants that survive and produce a lot of offspring in a given environment have high fitness, which by definition implies that such variants will become more common in the next generation; variants with fewer offspring will be encountered less frequently in the next generation. This is what is meant by differential selection: in a given environment, some variants will become more common over the generations, others will become less common. Features or variations that lead to high fitness in their environment are called adaptive (Mayr 2002). Of course, environments can and do change, implying that well-adapted organisms at one point in time may turn out to be very badly adapted to the new situation – 'maladapted', implying no more nor less than that they will become rarer over the generations.

This basic mechanism is key to explaining how humans and other living organisms evolved (Boyd and Silk 2009). The basic principles have also been applied to the evolution of culture (Richerson and Boyd 2005), although such application of evolutionary theory is still less widely accepted. The same holds for more recent models of gene-culture coevolution. Such models are being developed since it is becoming clear that culture has affected and is affecting the human genome (Laland et al. 2010) through processes such as niche construction (Kendal et al. 2011).

One of the reasons why evolutionary theory seems suitable as a general theoretical framework for human demography (and, more generally, the social sciences) is that it does justice to the fundamental contingency of human populations and societies. Evolutionary theory is not deterministic. Rather to the contrary: it is fundamentally probabilistic and acknowledges the fundamental contingency of life. Evolutionary theory does not allow to predict the substance of the future because it does not have information about the substantive direction. Instead, evolutionary theory contains of "a set of interacting mechanisms resulting in the production of variation and its selection" (Hammel and Howell 1987, p. 142).

Evolutionary theory is not teleological (Mayr 1961, 2002); there is no need to assume that evolution has a direction (in contrast to what has often been claimed, see, e.g., Lotka 1945) It does certainly not claim that evolution leads to perfection (even if we would know what perfection is), nor does it imply that things evolve to always get better – in biological evolution, organisms that may have thrived very well in one environment, may become extinct as the environment changes. Evolutionary theory is also not essentialist. Darwin had a hard time defending his populationist approach against the essentialist claims about the 'true' nature of different species (Mayr 1991, 2002).

Demography and populationist thinking is already playing an important role in evolutionary theory. "Human culture and biology jointly and collaboratively drive the evolution of human demography" (Levitis 2015, p. 415). Hammel and Howell (1987) called for an evolutionary theory "in which demographic events are the central mechanism and leading indicators of the coevolution of bodies, minds, and societies" (p.142). Recognizing that birth, marriage, migration, and death have both biological and cultural significance in any human society, and that the subject matter of demography is cutting across the sub-disciplines of the social and biological sciences, they argue that a demographically based formulation of evolutionary theory may integrate important aspects of cultural and biological evolution. More recently, Metcalf and Pavard (2007a) argued that "evolutionary biologists should be demographers" because evolution depends on fertility, migration, and mortality, as well as on population growth and structure; in other words: "All paths to fitness lead through demography" (Metcalf and Pavard 2007b). Therefore, evolutionary demography aims to cross barriers between social scientific and biological approaches to population processes by combining concepts and tools of demography and evolution, hoping to enhance the scope of both fields (Levitis 2015).

1.5.2 Agent-Based Modelling and the Evolutionary Approach

As indicated earlier, human populations are complex adaptive systems. Miller and Page (2007, pp. 78–89) discuss a range of characteristics of ABM that makes the approach particularly well suited to study such systems: the focus on dynamics and processes, the scalability and flexibility, the feasibility to model adaptive rather than optimizing agents, and the enhanced ability to address the role played by heterogeneity and variation. These features also make ABM particularly well suited as a tool to help developing an evolutionary approach in demography.

Agent-based models are inherently *dynamic*: even if one can take snapshots of the system's situation at discrete points in time, the results of the model change over time and the focus is drawn to the process at least as much as to the outcome. Like evolutionary theory, ABMs are inherently *process oriented*: the focus is on understanding the mechanisms that produce or reduce diversity and change. Evolutionary theory is about mechanisms rather than "laws", and ABM facilitates the investigation of mechanisms, where mechanisms can be considered halfway "between laws and descriptions" (Billari et al. 2003, p. 13).

Axelrod and Hamilton (1981) powerfully illustrate how a focus on dynamics may be crucial for our understanding. They showed how cooperation in populations may evolve even under conditions that, at any one point in time, imply no cooperation. A criticism by Venturini et al. (2015) on ABM maintains that it "cannot but confirm" individualistic behaviour and that it is unable to understand human cooperation. Indeed, in the first model developed by Axelrod and Hamilton, individual agents face a prisoner's dilemma that cannot be overcome in a single shot. Yet, when iterated over time, in a second model, cooperation emerges as a viable strategy (Venturini and colleagues seem to have missed this landmark paper). More generally, when developing a theoretical model, one can aim either at reproducing important features of the target system at a given point in time, or at modelling its evolution, i.e., at reproducing the changes that would occur *across generations*. Ideally, however, a good model should be able to reproduce both aspects of the phenomenon, and ABM facilitates such combination (Campennì and Schino 2014). In line with this, evolutionary demography involves investigating both how demographic processes evolve over time and the outcomes of such evolution (including population structure and composition) at given points in time.

Evolutionary demography not only involves integrating the cross-sectional and the longitudinal, it should also integrate insights gained at different levels of magnitude or scale and in diverging scholarly disciplines (from the molecular micro level of genetics to the macro level of human populations embedded in a globalizing society) (Kaplan and Gurven 2008). Demographic theory "thus faces the same issues raised by Darwinian population thinking: both observed population processes at a local scale and testable models at higher levels of aggregation are necessary, and theoretical formulations confined to one or the other are incomplete" (Kreager 2015a, p. 81). The *scalability* of ABMs and the *flexibility* of specifying agent behaviour and interactions are particularly useful here. The scalability refers to the ability of ABM to explore a system's behaviour both with a very low and a very high number of agents, and to switch the focus from micro- to macro-level system properties. The flexibility refers to the fact that ABMs can capture a very wide class of behaviours, which is particularly useful for implementing the insights from different study disciplines. Agents may, for example, respond to the constraints imposed by the human metabolic system as well as to the cultural rules implied by human society. Both kinds of rules can be specified in the same ABM, and the emerging properties can be studied at the level of individual agent behaviour, at the neighbourhood level, or at the population level. Mechanisms involved in multiple inheritance models, like the triple inheritance model involving genetic, ecological, and cultural inheritance (see Kendal et al. 2011) can be implemented explicitly in ABM. Change across generations can be simulated over thousands of generations, and snapshots can be taken at each point in time, enabling comparison with real-life data employing standard statistical tools.

Given the dynamic nature and flexibility of ABMs, agents can be designed to be *adaptive*, i.e., as learning from previous experiences within or across generations, or both. This allows moving away from the unrealistic, rationalistic, and atomistic models of well-informed agents who rationally processes all the relevant information to optimize behaviour to maximize utility (Miller and Page 2007, pp. 81–83). With ABM, it is possible to specify agents that learn, build networks, gain or lose power and influence, and inherit knowledge and resources from previous generations. The criticism that ABM is inherently atomistic and apolitical (Venturini et al. 2015) is therefore poorly targeted. For application to human demography, the model of adaptive rather than optimizing agents is much more consistent with evolutionary theory as well as with basic insights from psychology and sociology.

Finally, while conventional models often assume that the underlying agents have a high degree of homogeneity, where differences are typically described in terms of conditional averages, ABM facilitates to focus more on *heterogeneity* – even if it may turn out, empirically, that the aggregate system behaviour does not depend on the details of each agent (Miller and Page 2007, pp. 84–85). ABM does not require making any assumption about the homogeneity of agent populations, which is a key advantage given that heterogeneity is a core aspect of populations and population models (Billari et al. 2003, p. 12). While the focus of conventional statistical approaches is on how averages depend on a set of variables – an approach in the tradition of "the average man" (Quetelet 1835) – this may be insufficient to do justice to the role played by diversity and variation in explaining population patterns and change. Ernst Mayr even went so far as to imply that statistical methods do not really represent population thinking at all (Kreager 2015a, p. 78).

Enhancing the ability to address the role played by heterogeneity seems important for improving population theory, for example for improving demographic transition theory. In applications of ABM, it has become clear that a given outcome may be produced by different pathways or that a given pathway may lead to very different outcomes, depending on the size and composition of the population. Similarly, ABM has proven to be able to yield both results exemplifying convergent evolution (initially major differences in the population becoming smaller over time) as well as divergent evolution (minor initial differences that magnify over time and generations) (see Axelrod 1997). This matches very well with the observation that, while the transition from (moderately) high to low mortality and fertility in modern populations is a quite general phenomenon, uniform explanations in terms of macro-level factors and processes such as industrialisation, urbanisation, and modernisation have failed the empirical tests to a very large extent (Szreter 1993; Van Bavel 2010b; Watkins 1986).

For example, the secular decline of fertility got started under widely different economic conditions, unexplainable by standard modernisation theories, or failed to kick off when theory would have predicted this. Theories such as those developed by Frank Notestein spoke about interactions between the economy and populations largely at the macro level, without accounting for the heterogeneity within economies and populations. This approach “pushed key aspects of population variation and change to the margins” (Kreager 2015a, p. 79). Thanks to more detailed research in historical demography, often looking at very specific local communities and populations, it became clear that fertility and mortality decline can take place under widely differing conditions. This has stimulated the field to increasingly reconsider the role of local networks of communication in demographic change. In-depth study of local populations, conceived of in the ‘open’ rather than the ‘closed’ way, enabled us to understand more about the role played by distinctive environmental and cultural constraints existing prior to ‘big’ forces such as industrialization and modernization, implying that there is not one universal ‘transition’ pathway. The continuing diversity observed in demographic phenomena like ‘the’ demographic transition highlights that it will be key for demographic theory to understand the mechanisms that continue to renew population heterogeneity (Kreager 2015a, pp. 80–81), and ABM promises to be very helpful in gaining such understanding.

Acknowledgments The authors’ work on this chapter has received funding from the European Research Council under the European Union’s Seventh Framework Programme (FP/2007–2013)/ERC Grant Agreement no. 312290 for the GENDERBALL project.

References

Aparicio Diaz, A., Fent, T., Prskawetz, A., & Bernardi, L. (2011). Transition to parenthood: The role of social interaction and endogenous networks. *Demography, 48*(2), 559–579.

Axelrod, R. (1997). The dissemination of culture: A model with local convergence and global polarization. *Journal of Conflict Resolution, 41*(2), 203–226.

Axelrod, R., & Hamilton, W. D. (1981). The evolution of cooperation. *Science, 211*(4489), 1390–1396.

Bijak, J., Hilton, J., Silverman, E., & Cao, V. D. (2013). Reforging the wedding ring: Exploring a semi-artificial model of population for the United Kingdom with Gaussian process emulators. *Demographic Research, 29*, 729–765.

Billari, F. C. (2015). Integrating macro- and micro-level approaches in the explanation of population change. *Population Studies, 69*(S1), S11–S20.

Billari, F. C., Ongaro, F., & Prskawetz, A. (2003). Introduction: Agent-based computational demography. In F. C. Billari & A. Prskawetz (Eds.), *Agent-based computational demography – Using simulation to improve our understanding of demographic behaviour* (pp. 1–17). Heidelberg: Physica Verlag.

Billari, F. C., Prskawetz, A., Aparicio Diaz, B., & Fent, T. (2007). The "Wedding-Ring": An agent-based marriage model based on social interaction. *Demographic Research, 17*, 59–82.

Boyd, R., & Silk, J. B. (2009). *How humans evolved*. New York: W.W. Norton & Co.

Burch, T. K. (2003a). Demography in a new key: A theory of population theory. *Demographic Research, 9*, 263–284.

Burch, T. K. (2003b). Data, models, theory and reality: The structure of demographic knowledge. In F. C. Billari & A. Prskawetz (Eds.), *Agent-based computational demography – Using simulation to improve our understanding of demographic behaviour* (pp. 19–40). Heidelberg: Physica-Verlag.

Buss, D. M., Shackleford, T. K., Kirkpatrick, L. A., & Larsen, R. J. (2001). A half century of mate preferences: The cultural evolution of values. *Journal of Marriage and Family, 63*(2), 491–503.

Campennì, M., & Schino, G. (2014). Partner choice promotes cooperation: The two faces of testing with agent-based models. *Journal of Theoretical Biology, 344*, 49–55.

Charbit, Y. (2009). *Economic, social and demographic thought in the XIXth century: The population debate from Malthus to Marx*. Dordrecht: Springer.

Ciganda, D., & Villavicencio, F. (2016). Feedback mechanisms in the postponement of fertility in Spain. In A. Grow & J. Van Bavel (Eds.), *Agent-based modelling in population studies: Concepts, methods, and applications* (pp. 405–435). Springer.

Cointet, J.-P., & Roth, C. (2007). How realistic should knowledge diffusion models be? *Journal of Artificial Societies and Social Simulation, 10*(3), 5.

Coleman, J. S. (1986). Social theory, social research, and a theory of action. *American Journal of Sociology, 91*(6), 1309–1335.

Coleman, J. S. (1990). *Foundations of social theory*. Cambridge: Harvard University Press.

Courgeau, D., Bijak, J., Franck, R., & Silverman, E. (2016). Model-based demography: Towards a research agenda. In A. Grow & J. Van Bavel (Eds.), *Agent-based modelling in population studies: Concepts, methods, and applications* (pp. 29–51). Springer.

De Bruijn, B. J. (1999). *Foundations of demographic theory. Choice, process, context*. Amsterdam: Thela-Thesis.

Deconinck, H., Van Malderen, C., Speybroeck, N., Macq, J., & Chiem, J.-C. (2016). Agent-based modelling to inform health intervention strategies: The case of severe acute malnutrition in children in high-burden low-income countries. In A. Grow & J. Van Bavel (Eds.), *Agent-based modelling in population studies: Concepts, methods, and applications* (pp. 461–486). Springer.

Dublin, L. I., & Lotka, A. J. (1925). On the true rate of natural increase: As exemplified by the population of the united states, 1920. *Journal of the American Statistical Association, 20*(151), 305–339.

England, P., & McClintock, E. A. (2009). The gendered double standard of aging in US marriage markets. *Population and Development Review, 35*(4), 797–816.
Epstein, J. M. (2006). Agent-based computational models and generative social science. In J. M. Epstein (Ed.), *Generative social science: Studies in agent-based computational modeling* (pp. 4–46). Princenton: Princeton University Press.
Gray, J., Bijak, J., & Bullock, S. (2016). Deciding to disclose: A decision theoretic agent model of pregnancy and alcohol misuse. In A. Grow & J. Van Bavel (Eds.), *Agent-based modelling in population studies: Concepts, methods, and applications* (pp. 301–340). Springer.
Greitemeyer, T. (2007). What do men and women want in a partner? Are educated partners always more desirable? *Journal of Experimental Social Psychology, 43*(2), 180–194.
Grimm, V., Revilla, E., Berger, U., Jeltsch, F., Mooij, W. M., Railsback, S. F., et al. (2005). Pattern-oriented modeling of agent-based complex systems: Lessons from ecology. *Science, 310*(5750), 987–991.
Groeneveld, J., Klabunde, A., O'Brien, M. L., & Grow, A. (2016). How to describe agent-based models in population studies? In A. Grow & J. Van Bavel (Eds.), *Agent-based modelling in population studies: Concepts, methods, and applications* (pp. 237–254). Springer.
Grow, A. (2016). Regression metamodels for sensitivity analysis in agent-based computational demography. In A. Grow & J. Van Bavel (Eds.), *Agent-based modelling in population studies: Concepts, methods, and applications* (pp. 185–210). Springer.
Grow, A., & Van Bavel, J. (2015a). Assortative mating and the reversal of gender inequality in education in Europe: An agent-based model. *PLoS ONE, 10*(6), e0127806.
Grow, A., & Van Bavel, J. (2015b). *Too few alternatives? The reversal of the gender gap in education and its consequences for union stability*. Paper presented at the IUSSP Scientific Panel on Microsimulation and Agent-based Modelling in Demography/Max Planck Institute for Demographic Research workshop on "The Science of Choice – How to Model the Decision Making Process?"
Hammel, E. A., & Howell, N. (1987). Research in population and culture: An evolutionary framework. *Current Anthropology, 28*(2), 141–160.
Hedström, P. (2005). *Dissecting the social: On the principles of analytical sociology*. Cambridge: Cambridge University Press.
Hedström, P., & Swedberg, R. (1998). Social mechanisms: An introductory essay. In P. Hedström & R. Swedberg (Eds.), *Social mechanisms: An analytical approach to social theory* (pp. 1–31). Cambridge: Cambridge University Press.
Henrich, J., Heine, S. J., & Norenzayan, A. (2010). The weirdest people in the world? *The Behavioral and Brain Sciences, 33*(2–3), 61–83.
Hernes, G. (1972). The process of entry into first marriage. *American Sociological Review, 37*(2), 173–182.
Hernes, G. (1976). Diffusion and growth: The non-homogenous case. *Scandinavian Journal of Economics, 78*(3), 427–436.
Hilton, J., & Bijak, J. (2016). Design and analysis of demographic simulations. In A. Grow & J. Van Bavel (Eds.), *Agent-based modelling in population studies: Concepts, methods, and applications* (pp. 211–235). Springer.
Kaplan, H., & Gurven, M. (2008). Top-down and bottom-up research in biodemography. *Demographic Research, 19*, 1587–1602.
Kashyap, R., & Villavicencio, F. (2016). An agent-based model of sex ratio at birth distortions. In A. Grow & J. Van Bavel (Eds.), *Agent-based modelling in population studies: Concepts, methods, and applications* (pp. 343–367). Springer.
Kendal, J., Tehrani, J. J., & Odling-Smee, J. (2011). Human niche construction in interdisciplinary focus. *Philosophical Transactions of the Royal Society, B: Biological Sciences, 366*(1566), 785–792.
Kertzer, D. I., & Hogan, D. P. (1989). *Family, political economy, and demographic change: The transformation of life in Casalecchio, Italy, 1861–1921*. Madison: University of Wisconsin Press.

Kluge, F. A., & Vogt, T. C. (2016). Linking income, transfers, and social support in an agent-based family exchange model. In A. Grow & J. Van Bavel (Eds.), *Agent-based modelling in population studies: Concepts, methods, and applications* (pp. 439–459). Springer.

Klüsener, S., Scalone, F., & Dribe, M. (2016). Exploring the role of communication in shaping fertility transition patterns in space and time. In A. Grow & J. Van Bavel (Eds.), *Agent-based modelling in population studies: Concepts, methods, and applications* (pp. 369–403). Springer.

Kreager, P. (2009). Darwin and Lotka: Two concepts of population. *Demographic Research, 21*, 469–501.

Kreager, P. (2015a). Population and the making of the human sciences: A historical outline. In P. Kreager, B. Winney, S. Ulijaszek, & C. Capelli (Eds.), *Population in the human sciences. Concepts, models, evidence* (pp. 55–85). Oxford: Oxford University Press.

Kreager, P. (2015b). Population theory – A long view. *Population Studies, 69*(Supplement 1), S29–S37.

Laland, K. N., Odling-Smee, J., & Myles, S. (2010). How culture shaped the human genome: Bringing genetics and the human sciences together. *Nature Reviews Genetics, 11*(2), 137–148.

Levitis, D. A. (2015). Evolutionary demography: A synthesis of two population sciences. In J. D. Wright (Ed.), *International encyclopedia of the social & behavioral sciences, 2nd Ed.* (pp. 413–419). Oxford: Elsevier.

Lotka, A. J. (1945). The law of evolution as a maximal principle. *Human Biology, 17*(3), 167–194.

Lutz, W., & Goldstein, J. R. (2004). Introduction: How to deal with uncertainty in population forecasting? *International Statistical Review, 72*(1), 1–4.

Mayr, E. (1961). Cause and effect in biology. *Science, 134*(3489), 1501–1506.

Mayr, E. (1991). *One long argument. Charles Darwin and the genesis of modern evolutionary thought*. Cambridge: Harvard University Press.

Mayr, E. (2002). *What evolution is*. London: Phoenix.

Metcalf, C. J. E., & Pavard, S. (2007a). Why evolutionary biologists should be demographers. *Trends in Ecology and Evolution, 22*(4), 205–212.

Metcalf, C. J. E., & Pavard, S. (2007b). All paths to fitness lead through demography. *Trends in Ecology & Evolution, 22*(11), 563–564.

Miller, J. H., & Page, S. E. (2007). *Complex adaptive systems: An introduction to computational models of social life*. Princeton: Princeton University Press.

Prskawetz, A. (2016). The role of social interactions in demography: An agent-based modelling approach. In A. Grow & J. Van Bavel (Eds.), *Agent-based modelling in population studies: Concepts, methods, and applications* (pp. 53–72). Springer.

Quetelet, A. (1835). *Sur l'homme et le développement de ses facultés, ou essai de physique sociale*. Paris: Bachelier.

Richerson, P. J., & Boyd, R. (2005). *Not by genes alone. How culture transformed human evolution*. Chicago: The University of Chicago Press.

Richiardi, M., & Richardson, R. E. (2016). Agent-based computational demography and microsimulation using JAS-mine. In A. Grow & J. Van Bavel (Eds.), *Agent-based modelling in population studies: Concepts, methods, and applications* (pp. 75–112). Springer.

Schoen, R. (2006). *Dynamic population models*. Dordrecht: Springer.

Sear, R. (2015a). Evolutionary demography: A Darwinian renaissance in Demography. In J. D. Wright (Ed.), *International encyclopedia of the social & behavioral sciences, 2nd Ed.* (pp. 406–412). Oxford: Elsevier.

Sear, R. (2015b). Evolutionary contributions to the study of human fertility. *Population Studies, 69*(Supplement 1), S29–S55.

Skopek, J., Schulz, F., & Blossfeld, H.-P. (2011). Who contacts whom? Educational homophily in online mate selection. *European Sociological Review, 27*(2), 180–195.

Smaldino, P. E., & Schank, J. C. (2011). Human mate choice is a complex system. *Complexity, 17*(5), 11–22.

Szreter, S. (1993). The idea of demographic transition and the study of fertility change: A critical intellectual history. *Population and Development Review, 19*(4), 659–701.

Tabutin, D. (2007). Whither demography? Strengths and weaknesses of the discipline over fifty years of change. *Population, 62*(1), 15–31.

Todd, P. M., Billari, F. C., & Simão, J. (2005). Aggregate age-at-marriage patterns from individual mate-search heuristics. *Demography, 42*(3), 559–574.

Tsuya, N. O., Wang, F., Alter, G., & Lee, J. Z. (Eds.). (2010). *Prudence and pressure. Reproduction and human agency in Europe and Asia*. Cambridge: MIT Press.

Van Bavel, J. (2010a). Subreplacement fertility in the west before the baby boom: Past and current perspectives. *Population Studies, 64*(1), 1–18.

Van Bavel, J. (2010b). The decline of Belgian fertility in the nineteenth century. What have we learned since the Princeton project? In T. Eggerickx & J.-P. Sanderson (Eds.), *Chaire Quetelet 2005. Histoire de la population de la Belgique et de ses territoires* (pp. 429–461). Louvain-la-Neuve: Presses Universitaires de Louvain.

Vance, R. B. (1952). Is theory for demographers? *Social Forces, 31*(1), 9–13.

Venturini, T., Jensen, P., & Latour, B. (2015). Fill in the gap. A new alliance for social and natural sciences. *Journal of Artificial Societies and Social Simulation, 18*(2), 11.

Watkins, S. C. (1986). Conclusions. In A. J. Coale & S. C. Watkins (Eds.), *The decline of European fertility* (pp. 420–449). Princeton: Princeton University Press.

Willekens, F. J. (1990). Demographic forecasting: State-of-the-art and research needs. In C. A. Hazeu & G. A. B. Frinking (Eds.), *Emerging issues in demographic research* (pp. 9–66). Amsterdam: Elsevier Science.

Willekens, F. J. (2016). The decision to emigrate: A simulation model based on the theory of planned behaviour. In A. Grow & J. Van Bavel (Eds.), *Agent-based modelling in population studies: Concepts, methods, and applications* (pp. 257–299). Springer.

Williams, N. E., O'Brien, M. L., & Yao, X. (2016). Using survey data for agent-based modeling: design and challenges in a model of armed conflict and population change. In A. Grow & J. Van Bavel (Eds.), *Agent-based modelling in population studies: Concepts, methods, and applications* (pp. 159–184). Springer.

Wilson, T., & Rees, P. (2005). Recent developments in population projection methodology: A review. *Population, Space and Place, 11*(5), 337–360.

Wolfson, M., Gribble, S., & Beall, R. (2016). Exploring contingent inequalities: Building the theoretical health inequality model. In A. Grow & J. Van Bavel (Eds.), *Agent-based modelling in population studies: Concepts, methods, and applications* (pp. 487–513). Springer.

Zinn, S. (2016). Simulating synthetic life courses of individuals and couples, and mate matching. In A. Grow & J. Van Bavel (Eds.), *Agent-based modelling in population studies: Concepts, methods, and applications* (pp. 113–157). Springer.